SF 298 MASTER COPY KEEP THIS COPY FOR REPRODUCTION PURPOSES

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
4/19/96

3. REPORT TYPE AND DATES COVERED
FINAL REPORT

4. TITLE AND SUBTITLE
Novel Engineered Compound Semiconductor Heterostructures for Advanced Electronic and Optoelectronic Integrated Circuit Applications

5. FUNDING NUMBERS
DAAL03-92-G-0272

6. AUTHOR(S)
J. J. Coleman, N. Holonyak, Jr., G. E. Stillman

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
University of Illinois
Dept. of Elec. & Comp. Eng.
155 Everitt Laboratory
1406 W. Green St.
Urbana, IL 61801-2991

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 30595.1-EL-SDI

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

19960528 005

13. ABSTRACT (Maximum 200 words)

We have investigated novel semiconductor growth, materials, processes and devices. Gaseous source development for metalorganic molecular beam epitaxy (MOMBE) and metalorganic chemical vapor deposition (MOCVD) has been studied (Stillman). Silicon concentrations greater than 1×10^{19} cm^{-3} have been demonstrated using $SiBr_4$ by MOMBE and semi-insulating InP layers with resistivities greater than 1×10^8 Ω-cm have been produced by using CCl_4 by MOCVD. High power and high performance semiconductor lasers and laser arrays have also been studied (Coleman). Several advanced processing techniques including reactive ion etching and e-beam lithography have been used to fabricate these lasers. In addition, the development of selective area epitaxy by MOCVD enables integration of lasers with electrical components for optoelectronic circuits on a single chip. Finally, use of impurity induced layer disordering (IILD) and native oxides on high Al content compound semiconductors have been used to develop novel semiconductor laser devices (Holonyak). Microdisk lasers have been demonstrated using the IILD process to define curved geometry lasers. The native oxide has been used in vertical cavity surface emitting lasers VCSELs to define the current flow and to fabricate high-contrast distributed Bragg reflectors (DBRs).

14. SUBJECT TERMS
Native oxide, impurity induced layer disordering, optoelectronic integrated circuit, SiBr4 doping, CCl_4 doping

15. NUMBER IF PAGES
12

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

DTIC QUALITY INSPECTED 1

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

TABLE OF CONTENTS

ABSTRACT

We have investigated novel semiconductor growth, materials, processes and devices. Gaseous source development for metalorganic molecular beam epitaxy (MOMBE) and metalorganic chemical vapor deposition (MOCVD) has been studied (Stillman). Silicon concentrations greater than 1 x 10^{19} cm^{-3} have been demonstrated using $SiBr_4$ by MOMBE and semi-insulating InP layers with resistivities greater than 1 x 10^{8} Ω-cm have been produced by using CCl_4 by MOCVD. High power and high performance semiconductor lasers and laser arrays have also been studied (Coleman). Several advanced processing techniques including reactive ion etching and e-beam lithography, have been used to fabricate these lasers. In addition, the development of selective area epitaxy by MOCVD enables integration of lasers with electrical components for optoelectronic circuits on a single chip. Finally, use of impurity induced layer disordering (IILD) and native oxides on high Al content compound semiconductors have been used to develop novel semiconductor laser devices (Holonyak). Microdisk lasers have been demonstrated using the IILD process to define curved geometry lasers. The native oxide has been used in vertical cavity surface emitting lasers VCSELs to define the current flow and to fabricate high-contrast distributed Bragg reflectors (DBRs).

Studies at the University of Illinois under SDIO DAAL 03-92-G-0272 have focused on three areas of development related to the growth and characterization of optical semiconductor transmitters and detectors. These three thrust areas are described below and the significant work accomplished in each area is summarized.

Area 1 - Material Development

New materials critical for the development of optoelectronic devices and the techniques for producing these materials have been studied. These include InP and GaAs-based materials grown by both the chemical beam epitaxy (CBE) and the low-pressure metalorganic chemical vapor deposition technique (MOCVD). The use of CCl_4 as an extrinsic carbon doping source to produce p-type GaAs and InGaAs has been developed. In the CBE environment, CBr_4 has also been used to achieve carbon doped GaAs and InGaAs. Many devices including high speed HBTs and PIN photodetectors with a carbon doped base in both InP-based and GaAs-based materials have been demonstrated using this technology.

More recently, high resistivity InP epitaxial layers have been produced by flowing CCl_4 during growth at low temperature. These semi-insulating layers are easy to produce and do not have many of the harmful side effects of iron-doped semi-insulating layers. The potential applications for these layers includes use as a current blocking layer in semiconductor lasers, as a Shottky barrier enhancement layer in photodetectors and as buffer layers to isolate devices from the substrate or other devices. $SiBr_4$ has been developed as an alternative n-type dopant source of many III-V materials including GaAs, InGaP, InP and InGaAs. The doping efficiency of this source is much higher than that of other silicon sources used in CBE growth. For InP growth, carrier concentrations in excess of 1×10^{19} cm^{-3} have enabled the use of an InP contacting layers in an HBT rather than InGaAs contact layers. This simplifies the growth of InP-based HBTs and results in a transparent emitter structure allowing topside illumination.

Area 1 - Results

The most important results obtained in this objective were

1. Development of CCl_4 and CBr_4 doping of GaAs and InGaAs. These extrinsic doping sources give much better control and range in doping levels than previous methods used for carbon doping.

2. Development of InGaP/GaAs and InP/InGaAs HBTs with a carbon doped base. Carbon doped base HBTs have much better reliability than HBTs that use a Zn- or Be-doped base. In addition, extremely abrupt doping profiles and high doping levels are possible when using carbon as the base dopant.

3. Development of semi-insulating epitaxial InP using CCl_4 at low growth temperature. The simplicity of the growth of these layers and the lack of harmful side effects such as memory effects or migration during subsequent growths make these layers attractive in many applications where iron-doped InP is currently being used.

4. Development of $SiBr_4$ doping. The high incorporation efficiency of this is extremely useful in CBE growth. HBT using $SiBr_4$ for the n-type doping and CBr_4 for p-type doping have been demonstrated.

Area 2 - High Power Lasers and Laser Arrays

A large number of high power and high performance semiconductor lasers and laser arrays were studied as a part of this program. These included high power laser diode arrays, strained-layer distributed feedback ridge waveguide quantum well heterostructure lasers and arrays, strained-layer quantum well heterostructure circular ring lasers, reactive ion etched corner reflector strained-layer InGaAs-GaAs-AlGaAs quantum well lasers, and ridge waveguide distributed Bragg reflector InGaAs/GaAs quantum well lasers.

Area 2 - Results

The most important results obtained under this objective were

1. Nonplanar periodic laser arrays are suitable for very high power phase-locked operation and relatively simple to fabricate.
2. A form of a surface-processed ridge waveguide DFB laser can be made using direct write electron beam lithography and reactive ion etching. These lasers and similar arrays have very interesting characteristics but a better, simpler version involves using the same processes to form a deeply etched distributed Bragg reflector (DBR) laser structure.
3. Selective area metalorganic chemical vapor deposition (MOCVD) growth processes can be used to design the quantum well thickness and, hence, transition energy, anywhere on a wafer using simple low resolution oxide masking. These structures are suitable for low threshold buried heterostructure lasers and a variety of integrated photonic structures.

Area 3 - Impurity-Induced Layer Disordering and Native Oxide Formation of Al-bearing III-V Compounds

Impurity-induced layer disordering (IILD) and the selective oxidation of Al-bearing III-V materials are powerful processing technologies which were discovered at the Solid State Devices Laboratory. These technologies allow nearly planar, selective conversion of semiconductor material to material with distinctly different material properties, useful in defining device geometries. Using IILD to intermix heterolayers, the energy band gap, index of refraction and

conductivity of a material can be selectively altered. Native oxidation of Al-bearing III-V's converts semiconductor material into an insulating material which has a low index of refraction and improved surface passivation properties. These layers are useful in many optical devices.

Area 3 - Results

The most important results obtained under this objective were

1. The IIID and native oxide technologies have been used to define curved geometry lasers. Micro disk (10 μm diameter and less than 1 μm thick) laser geometries have been fabricated and optically excited. Additionally, very low threshold ring laser diodes with small (200 μm) diameters have been demonstrated.

2. The native oxide has been used to define current flow in lasers with buried heterolayers and it has been used to fabricate high-contrast distributed Bragg reflecting mirrors used in VCSEL's and in thin cavity edge emitting laser diodes.

3. The native oxide has demonstrated a surface passivation effects that has led to enhanced device lifetimes in light emitters.

4. The native oxide technology has been used to demonstrate an enhancement mode MOSFET in the AlGaAs/GaAs material system.

5. IILD and native oxide technologies have been used to define the geometries of low-threshold, index and gain-guided stripe laser diodes. These technologies have also been used to fabricated coupled stripe laser diodes.

Personnel and Degrees Earned

Kevin Beernink	Ph.D.	1993
Eugen Chen	M.S.	1993
Timothy Cockerill	Ph.D.	1993
Carolyn Colomb	Ph.D.	1993
Tony Curtis		
Nada El-Zein	Ph.D.	1995
Micheal Fresina	M.S.	1993
David Forbes	Ph.D.	1995
Nathan Gardner	Ph.D.	1995
Allen Hanson	Ph.D.	1994
Timothy Horton		
Steven Jackson	Ph.D.	1994
Andrew Jones M.S.	1995	
Mike Krames	Ph.D.	1995
Robert Lammert	M.S.	1995
Xiuling Li		
Steve Maranowski	Ph.D.	1995
Mike Ries	M.S.	1993
Steven Stockman	Ph.D.	1993

Area 1 - Publications

Cunningham, B.T., L.J. Guido, J.E. Baker, J.S. Major, Jr., N. Holonyak, Jr., and G.E. Stillman. Carbon diffusion in undoped, n-type, and p-type GaAs. *Appl. Phys. Lett.* **55**, 687-698, 14 Aug 1989.

Cunningham, B.T., Stillman, G.E., and G.S. Jackson. Carbon-doped base GaAs/AlGaAs heterojunction bipolar transistor grown by metalorganic chemical vapor deposition using carbon tetrachloride as a dopant source. *Appl. Phys. Lett.* **56**, 361-363, 22 Jan 1990.

Guido, L.J., J.S. Major, Jr., J.E. Baker, N. Holonyak, Jr., B.T. Cunningham, and G.E. Stillman. Column III-Column V sublattice interaction via Zn- and Si impurity-induced layer disordering of ^{13}C-doped $Al_xGa_{1-x}As$-GaAs superlattice. *Appl. Phys. Lett.* **56**, 572-574, 5 Feb 1990.

Cunningham, B.T., J.E. Baker, and G.E. Stillman. Carbon tetrachloride doped $Al_xGa_{1-x}As$ grown by metalorganic chemical vapor deposition. *Appl. Phys. Lett.* **56**, 836-838, 26 Feb 1990.

Cunningham, B.T., J.E. Baker, and G.E. Stillman. Carbon tetrachloride doped $Al_xGa_{1-x}As$ grown by metalorganic chemical vapor deposition. *J. Electron. Mater.* **19**, 331-335, 1990.

Cunningham, B.T., J.E. Baker, S.A. Stockman, and G.E. Stillman. Absence of ^{13}C incorporation in $^{13}CCl_4$-doped InP grown by metalorganic chemical vapor deposition. *Appl. Phys. Lett.* **56**, 1760-1762, 30 April 1990.

Guido, L.J., B.T. Cunningham, D.W. Nam, K.C. Hsieh, W.E. Plano, J.S. Major, Jr., E.J. Vesely, A.R. Sugg, N. Holonyak, Jr., and G.E. Stillman. Al-Ga interdiffusion in heavily carbon-doped $Al_xGa_{1-x}As$-GaAs quantum well hetero-structures. *J. Appl. Phys.* **67**, 2179-2182, 15 Feb 1990.

Colomb, C.M., S.A. Stockman, S. Varadarajan, and G.E. Stillman. Minority carrier transport in carbon doped gallium arsenide. *Appl. Phys. Lett.* **60**, 65-67, 6 Jan 1992.

Szafranek, I., M. Szafranek, and G.E. Stillman. Mechanism of light-induced reactivation of acceptors in p-type hydrogenated gallium arsenide. *Phys. Rev. B* **45**, 6497-6508, 15 March 1992.

Stockman, S.A., A.W. Hanson, and G.E. Stillman. Growth of carbon-doped p-type $In_xGa_{1-x}As$ ($0 < x \leq 0.53$) by metalorganic chemical vapor deposition. *Appl. Phys. Lett.* **60**, 2903-2905, 8 June 1992.

Hanson, A.W., S.A. Stockman, and G.E. Stillman. $InP/In_{0.53}Ga_{0.47}As$ heterojunction bipolar transistors with a carbon-doped base grown by MOCVD. *IEEE Electron Device Lett.* **13**, 504-506, Oct 1992.

Stockman, S.A., A.W. Hanson, S.M. Lichtenthal, M.T. Fresina, G.E. Höfler, K.C. Hsieh, and G.E. Stillman. Passivation of carbon acceptors during growth of carbon-doped GaAs, InGaAs and HBT's by MOCVD. *J. Electron. Mater.* **21**, 1111-1118, 1992.

Stillman, G.E., S.A. Stockman, A.W. Hanson, C.M. Colomb, M.T. Fresina, and S.T. Uribe. Carbon-doped InGaAs grown by MOCVD for InP/InGaAs heterojunction bipolar transistors. Paper presented at *International Symposium on GaAs and Related Compounds*, Inst. Phys. Conf. Ser., No. 129, Karuizawa, 1992 pp. 687-692.

Stockman, S.A., A.W. Hanson, S.L. Jackson, J.E. Baker, G.E. Stillman. Effect of post-growth cooling ambient on acceptor passivation in carbon-doped GaAs grown by metalorganic chemical vapor deposition. *Appl. Phys. Lett.* **62**, 1248-1250, 15 March 1993.

Hanson, A.W., S.A. Stockman, and G.E. Stillman. Comparison of $In_{0.5}Ga_{0.5}P$/GaAs single-and double-heterojunction bipolar transistors with a carbon-doped base. *Electron Device Lett.* **14**, 25-28, 1 Jan 1993.

Colomb, C.M., S.A. Stockman, N.F. Gardner, A.P. Curtis, G.E. Stillman, T.S. Low, D.E. Mars, and D. B. Davito. Zero-field time-of-flight characterization of minority-carrier transport in heavily carbon- doped GaAs. *J. Appl. Phys.* **73**, 7471-7477, 1 June 1993.

Jackson, S.L., J.N. Baillargeon, A.P. Curtis, X. Liu, J.E. Baker, J.I. Malin, K.C. Hsieh, S.G. Bishop, K.Y. Cheng, and G.E. Stillman. Generation of fast-switching As_2 and P_2 beams from AsH_3 and PH_3 for gas-source molecular-beam epitaxial growth of InGaAs/InP multiple quantum well and superlattice structures. *J. Vac. Sci. Technol.* **B11**, 1045-1049, May/June 1993.

Stockman, S.A., M.T. Fresina, Q.J. Hartmann, A.W. Hanson, N.F. Gardner, J.E. Baker, and G.E. Stillman. Carbon incorporation in InP grown by metalorganic chemical vapor deposition and application to InP/InGaAs heterojunction bipolar transistors. *J. Appl. Phys.* **75**, 4233-4236, 15 April 1994.

Jackson, S.L., M.T. Fresina, J.E. Baker, and G.E. Stillman. High-efficiency silicon doping of InP and $In_{0.53}Ga_{0.47}As$ in gas source and metalorganic molecular beam epitaxy using silicon tetrabromide. *Appl. Phys. Lett.* **64**, 2867-2869, 23 May 1994.

Stockman, S.A. A.W. Hanson, C.M. Colomb, M.T. Fresina, J.E. Baker and G.E. Stillman. A comparison of TMGa and TEGa for low-temperature metalorganic chemical vapor deposition growth of CCl_4-doped InGaAs. *J. Electron. Mater.* **23**, 791-799, 1994.

Gardner, N.F., Q.J. Hartmann, S.A. Stockman, G.E. Stillman, J.E. Baker, J.I. Malin, and K.C. Hsieh. Semi-insulating InP grown at low temperature by metalorganic chemical vapor deposition. *Appl. Phys. Lett.* **65**, 359-361, 18 July 1994.

Stillman, G.E., S.A. Stockman, C.M. Colomb, A.W. Hanson, and M.T. Fresina. Carbon doping of InGaAs for device applications. 1994 *Mater. Res. Soc. Symposium Proceedings* **325**, 197-208, 1994.

Stockman, S.A. and G.E. Stillman. Hydrogen in III-V device structures. 1994 *Materials Science Forum* **148-149**, 501-536, 1994.

Fresina, M.T., S.L. Jackson, and G.E. Stillman. InP/InGaAs HBTs with n^+-InP contacting layers grown by MOMBE using $SiBr_4$. *Electronics Letters*, **30** 2177-2178, 8 Dec 1994.

Jackson, S.L., S. Thomas, M.T. Fresina, D.A. Ahmari, J.E. Baker, and G.E. Stillman. Silicon doping on InP, GaAs, $In_{0.53}Ga_{0.47}As$ and $In_{0.49}Ga_{0.51}P$ grown by gas source and metalorganic molecular beam epitaxy using a $SiBr_4$ vapor source. *Proceedings Sixth International Conf. on InP and Related Materials*, Santa Barbara, CA, March 27-31, 1994, pp. 57-60.

Gardner, N.F., Q.J. Hartmann, S.A. Stockman, N. Pan, and G.E. Stillman. Semi-insulating CCl_4-doped InP grown at low temperature by LP-MOCVD. *Proceedings Sixth International Conf. on InP and Related Materials*, Santa Barbara, CA, March 27-31, 1994, pp. 61-63.

Gardner, N. F., Q. J. Hartmann, J. E. Baker, and G. E. Stillman, The effect of growth temperature on the electrical properties of CCl_4-doped semi-insulating InP. *Appl. Phys. Lett.* **67**, 3004-3006,1995.

Area 2 - Publications

High power pulsed operation of an optimized nonplanar corrugated substrate periodic laser diode array, R P Bryan, L M Miller, T M Cockerill, S M Langsjoen and J J Coleman, *IEEE J. Quantum Electron.* **26**, 222 (1990)

Temperature dependence of compositional disordering of GaAs-AlAs superlattices during MeV Kr irradiation, R P Bryan, L M Miller, T M Cockerill, J J Coleman, J L Klatt and R S Averback, *Phys. Rev. B15*, **41**, 3889 (1990)

Characteristics of step graded separate confinement quantum well lasers with direct and indirect barriers, L M Miller, K J Beernink, T M Cockerill, R P Bryan, M E Favaro, J Kim, J J Coleman and C M Wayman, *J. Appl. Phys.***68**, 1964 (1990)

Temperature dependence of compositional disordering of GaAs-AlAs superlattices during MeV Kr irradiation, R P Bryan, L M Miller, T M Cockerill, J J Coleman, J L Klatt and R S Averback, *Mat. Res Soc. Proc.* **198**, 79 (1990)

In-phase operation of high power nonplanar periodic laser arrays, R P Bryan, T M Cockerill, L M Miller, T K Tang, T A DeTemple and J J Coleman, *Appl. Phys. Lett.* **58**, 113 (1991)

Differential gain in bulk and quantum well diode lasers, C A Zmudzinski, P S Zory, G G Lim, L M Miller, K J Beernink, T L Cockerill, J J Coleman, C S Hong and L Figueroa, *IEEE Trans. Photonics Tech. Lett.* **3**, 1057 (1991)

A self consistent model of a nonplanar quantum well periodic laser array, S M Lee, S L Chuang, R P Bryan, C A Zmudzinski and J J Coleman, *J. Quantum Electron.* **27**, 1886 (1991)

InGaAs-GaAs-AlGaAs strained-layer distributed feedback ridge waveguide quantum well heterostructure laser array, L M Miller, K J Beernink, J T Verdeyen, J J Coleman, J S Hughes, G M Smith, J Honig and T M Cockerill, *Electronics Lett.* **27**, 1943 (1991)

Depressed index cladding graded barrier separate confinement single quantum well heterostructure laser, T M Cockerill, J Honig, T A DeTemple and J J Coleman, *Appl. Phys. Lett.* **59**, 2694 (1991)

Phase-locked ridge waveguide InGaAs-GaAs-AlGaAs strained-layer quantum well heterostructure laser arrays, K J Beernink, L M Miller, T M Cockerill and J J Coleman, *Appl. Phys. Lett.* **59**, 3222 (1991)

Bending loss in optical waveguides for nonplanar laser array applications, S M Lee, W C Chew, S L Chuang and J J Coleman, *J. Appl. Phys.* **71**, 2513 (1992)

Characterization of an InGaAs-GaAs AlGaAs strained layer distributed feedback ridge waveguide quantum well heterostructure laser, L M Miller, K J Beernink, J T Verdeyen, J J Coleman, J S Hughes, G M Smith, J Honig and T M Cockerill, *Photonics Tech. Lett.* **4**, 296 (1992)

Effect of design variations on the threshold current density of AlGaAs separate confinement heterostructure single quantum well lasers, M E Givens, L M Miller and J J Coleman, *J. Appl. Phys.*, **71**, 4583 (1992)

Strained-layer quantum well heterostructure lasers, J J Coleman, *Thin Solid Films* **216**, 68 (1992)

$In_xGa_{1-x}As$-$Al_yGa_{1-y}As$-GaAs strained-layer quantum well heterostructure circular ring lasers, H Han, M E Favaro, D V Forbes and J J Coleman *Photonics Tech. Lett.* **4**, 817 (1992)

Threshold current density in strained layer $In_xGa_{1-x}As$-GaAs quantum well heterostructure lasers, J J Coleman, K J Beernink, and M E Givens, *IEEE J. Quantum Electron.* **28**, 1983 (1992)

Characterization of electrical and optical loss of MOCVD regrowth in strained layer InGaAs-GaAs quantum well heterostructure lasers, T M Cockerill, J Honig, D V Forbes, K J Beernink and J J Coleman, *J. Crystal Growth* **124**, 553 (1992)

Four wavelength distributed feedback ridge waveguide quantum well heterostructure laser array, L M Miller, K J Beernink, J S Hughes, S G Bishop and J J Coleman, *Appl. Phys. Lett.* **61**, 2964 (1992)

A distributed feedback strained layer quantum well heterostructure 980 nm laser fabricated by two-step metalorganic chemical vapor deposition, T M Cockerill, J Honig, D V Forbes and J J Coleman, *Appl. Phys. Lett.* **62**, 820 (1993)

Monolithic integration of a strained layer InGaAs-GaAs-AlGaAs quantum well laser with a passive waveguide by selective-area MOCVD, T M Cockerill, D V Forbes, H Han and J J Coleman, *Photonics Tech. Lett.* **5**, 448 (1993)

Strained layer quantum well heterostructure lasers, J J Coleman, *Quantum Well Lasers*, P S Zory, Jr. ed. (Academic Press, Inc., Cambridge, MA, 1993)

Optical properties of reactive ion etched corner reflector strained-layer InGaAs-GaAs-AlGaAs quantum well lasers, G M Smith, D V Forbes, J J Coleman and J T Verdeyen, *IEEE Photon. Tech. Lett.* **5**, 873 (1993)

Wavelength tuning in strained layer InGaAs-GaAs-AlGaAs quantum well lasers by selective-area MOCVD, T M Cockerill, D V Forbes, H Han, B A Turkot, J A Dantzig, I M Robertson and J J Coleman, *J. Electronic Mater.* **23**, 115 (1994)

Experimental gain characteristics and barrier lasing in strained-layer InGaAs-GaAs-AlGaAs quantum well heterostructure lasers, J J Coleman and K J Beernink, *J. Appl. Phys.* **75**, 1879 (1994)

A corner reflector InGaAs-GaAs strained layer single quantum well coupled laser array, Z J Fang, G M Smith, D V Forbes and J J Coleman, *IEEE Photon. Tech. Lett.* **6**, 10 (1994)

Strained layer quantum well heterostructure lasers by metalorganic chemical vapor deposition (MOCVD), J J Coleman, T M Cockerill and D V Forbes, *Proceedings of the Conference on Optoelectronic Materials and Devices*, p. 1 (1994)

Ridge waveguide distributed Bragg reflector InGaAs/GaAs quantum well lasers, G M Smith, J S Hughes, M L Osowski, D V Forbes and J J Coleman, *Electronics Lett.* **30**, 651 (1994)

Advances in quantum well heterostructure lasers: Strained-layer buried heterostructure lasers by selective area epitaxy, J J Coleman, T M Cockerill, D V Forbes and J A Dantzig, *SPIE Laser-Diode Technology and Applications VI*, **2148**, 158 (1994)

Strained layer InGaAs-GaAs-AlGaAs buried heterostructure quantum well lasers by three-step selective-area metalorganic chemical vapor deposition, T M Cockerill, D V Forbes, J A Dantzig and J J Coleman, *IEEE J. Quantum Electron.* **30**, 441 (1994)

Twelve-channel strained layer InGaAs-GaAs-AlGaAs buried heterostructure quantum well laser array for WDM applications by selective-area MOCVD, T M Cockerill, R M Lammert, D V Forbes, M L Osowski and J J Coleman, *IEEE Photon. Tech. Lett.* **6**, 786 (1994)

Area 3 - Publications

T. A. Richard, S. A. Maranowski, N. Holonyak, Jr., E. I. Chen, M. J. Ries, J. G. Neff, P. A. Grudowski, and R. D. Dupuis, "Enhanced Hot-Carrier Spontaneous and Stimulated Recombination in a Photopumped Vertical Cavity $Al_xGa_{1-x}As$-GaAs Quantum Well Heterostructure With Multiple Top and Bottom Native Oxide Mirrors," Appl. Phys. Lett. 66, 589-591 (30 Jan 1995).

N. Holonyak, Jr., "From Carbide Lamps to Semiconductor Lamps: The Light Emitting Diode (LED)," BRIDGE of Eta Kappa Nu, Vol. 91 (#2), pp. 4-10 (Feb 1995).

M. R. Krames, E. I. Chen, N. Holonyak, Jr., A. C. Crook, T. A. DeTemple, P.-A. Besse, "Deep-Oxide Planar Buried-Channel AlGaAs-GaAs Quantum Well Heterostructure Waveguides With Low Bend Loss," Appl. Phys. Lett. 66, 1912-1914 (10 April 1995).

E. I. Chen, N. Holonyak, Jr., and S. A. Maranowski, "$Al_xGa_{1-x}As$-GaAs Metal-Oxide Semiconductor Field Effect Transistors Formed by Lateral Water Vapor Oxidation of AlAs," Appl. Phys. Lett. 66, 2688-2690 (15 May 1995).

A. L. Holmes, M. R. Islam, R. V. Chelakara, F. J. Ciuba, R. D. Dupuis, M. R. Ries, E. I. Chen, S. A. Maranowski, and N. Holonyak, Jr., "High-Reflectivity Visible-Wavelength Semiconductor-Native Oxide Bragg Reflectors Grown by Metalorganic Chemical Vapor Deposition," Appl. Phys. Lett. 66, 2831-2833 (22 May 1995).

T. A. Richard, N. Holonyak, Jr., F. A. Kish, M. R. Keever, and C. Lei, "Postfabrication Native-Oxide Improvement of the Reliability of Visible-Spectrum AlGaAs-In(AlGa)P p-n Heterostructure Diodes," Appl. Phys. Lett. 66, 2972-2974 (29 May 1995).

M. R. Krames, A. D. Minervini, and N. Holonyak, Jr., "Deep-Oxide Curved Resonator for Low-Threshold AlGaAs-GaAs Quantum Well Heterostructure Ring Lasers," Appl. Phys. Lett. 67, 73-75 (3 July 1995).

N. Holonyak, Jr., "From Si to Alloy Compound Semiconductors: The Light Emitting Diode and Lamp," Japan Prize Commemorative Lecture, 26 April 1995.

M. J. Ries, N. Holonyak, Jr., E. I. Chen, S. A. Maranowski, M. R. Islam, A. L. Holmes, and R. D. Dupuis, "Visible-Spectrum (λ=650 nm) Photopumped (Pulsed, 300 K) Laser Operation of a Vertical-Cavity AlAs-AlGaAs/InAlP-InGaP Quantum Well Heterostructure Utilizing Native Oxide Mirrors," Appl. Phys. Lett. 67, 1108-1109 (21 Aug 1995).

M. R. Krames, A. D. Minervini, E. I. Chen, N. Holonyak, Jr., and J. E. Baker, "Improved Thermal Stability of AlGaAs-GaAs Quantum Well Heterostructures Using a "Blocking" Zn Diffusion to Reduce Column-III Vacancies," Appl. Phys. Lett. 67, 1859-1861 (25 Sept 1995).

P. W. Evans, N. Holonyak, Jr., S. A. Maranowski, M. J. Ries, and E. I. Chen, "Edge Emitting Quantum Well Heterostructure Laser Diodes With Auxiliary Native Oxide Vertical Cavity Confinement," Appl. Phys. Lett. 67, 3168-3170 (20 Nov 1995).

1995 Patents

M. J. Ludowise, N. Holonyak, Jr., S. J. Caracci, M. R. Krames, and F. A. Kish, U.S. Patent #5,400,354, March 21, 1995, "LAMINATED UPPER CLADDING STRUCTURE FOR A LIGHT EMITTING DEVICE" (Filed February 9, 1994; Serial #08-193,681).

Nick Holonyak, Jr., F. A. Kish, and S. J. Caracci, U.S. Patent #5,403,775, April 4, 1995, "METHOD OF MAKING SEMICONDUCTOR DEVICES AND TECHNIQUES FOR CONTROLLED OPTICAL CONFINEMENT" (Filed June 15, 1994).

N. Holonyak, Jr., N. El-Zein, F. A. Kish, U. S. Patent #5,425,043, June 13, 1995, "SEMICONDUCTOR LASER" (Filed August 9, 1994; Division of Ser. No. 927 822, August 10, 1992, Patent # 5,353,295).

N.F. Gardner, S.A. Stockman, Q.J. Hartmann, and G.E. Stillman, filed March 21, 1995, titled "HALIDE DOPANT PROCESS FOR PRODUCING SEMI-INSULATING GROUP II-V REGIONS FOR SEMI-CONDUCTOR DEVICES" (Filed March 24, 1995; USSN 410,782).

S.L. Jackson and G.E. Stillman, filed March 27, 1995, titled "VAPOR-SOURCE SILICON DOPING OF EPITAXIALLY-GROWN III-V COMPOUND AND ALLOY SEMICONDUCTORS USING SILICON TETRABROMIDE"(Filed March 27, 1995; USSN 410,803).